Charting a Course Toward Diagnostic Monitoring: A Continuing Review of Coral Reef Attributes and a Research Strategy for Creating Coral Reef Indexes of Biotic Integrity

by

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Abstract

This paper continues our review of coral reef attributes and presents a research strategy for creating coral reef indexes of biotic integrity (IBI's) that, once developed, can be used in coral reef biocriteria programs and for the diagnostic monitoring of coral reefs around the world. A framework for the definition of coral reef multimetric indexes is provided and we demonstrate how existing research fits into this framework. The research strategy has 6 components; sessile epibenthos, benthic macroinvertebrates, fish, macrophytes, phytoplankton and zooplankton. The research strategy is based on our best judgement, other expert opinion, and available information. It draws on techniques that have been successful in freshwater, estuarine, and temperate marine biocriteria programs and outlines those that will likely be successful in coral reef environments. Understanding the tolerance and intolerance of coral reef taxa to specific, as well as combinations, of chemical pollutants and other human influences will be crucial in creating effective IBI's. We emphasize that this research strategy is just a starting point. The attributes, their response specificity, and their predicted response must be specified by pilot program research. It is hoped that this strategy will stimulate research in the development of coral reef IBI's and produce new ideas and results that will move this important endeavor forward. Additional steps required include development of a coral reef classification system and selection and sampling of minimally disturbed sites to define reference condition or regional ecological expectations.

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Introduction

The purpose of this paper is to continue our review of coral reef attributes (Jameson et al. 1998) and to present a research strategy for creating coral reef indexes of biotic integrity (IBIs) (Karr and Chu, 1999). Once developed, IBIs can be used in coral reef biocriteria programs (Jameson et al. 1998) for diagnostic monitoring of coral reefs around the world. The following research strategy is based on our best judgement, other expert opinion, and available information. It draws on techniques that have been successful in freshwater, estuarine and temperate marine biocriteria programs and outlines those that will likely be successful in coral reef environments. We emphasize that this research strategy is just a starting point. The attributes, their response specificity, and their predicted response may require revision based upon results of pilot program research. It is hoped that this strategy will stimulate research in the development of coral reef IBIs and produce new ideas and results that will move this important endeavor forward. Table 1 provides definitions for key terms used in this paper.

Table 1. Key terms used in defining biological condition (adapted from Karr and Chu, 1999).

Term	Definition
Endpoint	A measured characteristic that indicates the condition of a biological, chemical or physical system
Attribute	Measurable part or process of a biological system
Metric	Attribute empirically shown to change in value along a gradient of human influence (i.e., a dose-response context is documented and confirmed)
Multimetric index	An index (expressed as a single numerical value) that integrates several biological metrics to indicate a site's condition (ex., an index of biotic integrity - IBI)
Biological monitoring	Sampling the biota of a place (i.e., coral reef)
Biological assessment	Using samples of living organisms to evaluate the condition of places

Biological integrity	The condition at sites able to support and maintain a balanced, integrated, and adaptive biological system having the full range of elements and processes expected for a region. Biological integrity is the product of ecological and evolutionary processes at a site in the relative absence of human influence (Karr 1996)
Biocriteria (biological criteria)	Criteria which define a desired biological condition for a water body and can be used to evaluate the biological integrity of the water body. When adopted by states, they become legally enforceable standards (narrative expressions or numerical values)
Designated aquatic life use	Descriptions of the optimal use of each waterbody as defined by states (i.e., natural, fisheries, recreational, transportation, or mixed use)

Where Are We?

Coral Reefs Are Losing Their Living Components

Coral reefs continue to deteriorate as a result of human society's actions; devastation is obvious, even to the untrained eye (Ginsburg, 1994; Jameson et al., 1995; Bryant et al., 1998; Hodgson, 1999). Human impacts decrease ecosystem resiliency to natural change. In 1997-1998 the global coral reef monitoring network and volunteer groups like Reef Check observed the most severe bleaching event in history (Wilkinson, 1998; Hodgson, 1999). They continue to monitor to see if these corals will recover or die and if damaged ecosystems will recuperate. Marine protected areas, such as Jamaica's Montego Bay Marine Park, are struggling to keep land-based sources of pollution from killing their reefs (Huber and Jameson, 1998; 1999; 2000; Jameson and Williams, 2000). From 1992 to 1997 they have seen coral-smothering algal cover increase dramatically and over-fishing has wiped-out critical grazing fish populations (Sullivan and Chiappone, 1994; Williams and Polunin, in press). Even regions with good water quality, like the Red Sea and Gulf of Aqaba, are fighting to keep anchor and fishing gear damage from physically pulverizing their valuable coral resources (Jameson, 1998; Jameson et al., 1999; Fadlallah, 1999).

Other less visible, but potentially more devastating threats include increased atmospheric carbon dioxide concentrations that could decrease oceanic pH and carbonate ion concentrations and result in reduced coral calcification rates (Kleypas et al., 1999). These oceanic chemical changes, combined with other stresses such as, elevated temperatures and bleaching, could kill corals on a global scale (Buddemeier, 1999). Further studies at the ecosystem level will help to verify this hypothesis.

Society Can Not Afford To Lose The Economic Benefits Of Coral Reefs

Coral reefs are some of the most diverse, valuable, and vulnerable marine habitats on the earth. They provide millions of people with food, tourism revenue, coastal protection and new medications for increasingly drug-resistant diseases — despite being among the least monitored and protected natural habitats in the world. Tens of thousands of species have been identified on coral reefs, and estimates suggest that coral reefs may be home to more than nine million species of plants and animals (Bryant et al., 1998). The magnitude of fish harvests per unit area from coralline shelves approximates those taken by trawlers from temperate shelves and it is estimated (conservatively) that the potential global annual harvest from tropical reef fisheries is 6 million metric tons (Munro, 1996). Over half of all managed fishery species in the United States spend important parts of their lives on or around coral reefs (USCRTF, 1999). Some of the most promising biotechnological innovations in the future may come from coral reef species. As much as 90% of the animal protein consumed on many Pacific Islands comes from marine sources (IUCN, 1993). Tourism, commercial, recreational, and subsistence fishing, and the protection of coastal communities and ports from storms, provide economic benefits estimated to be in excess of $375 billion per year worldwide (Costanza et al. 1997). In 1990 the coral reefs of Florida alone have been estimated to generate about $US1.6 billion from recreation uses (USDOC, 1994). In the Caribbean, tourism generates up to 30% of investment and GDP (Dixon et al., 1993; Hill 1998). In 1990, Caribbean tourism earned $US8.9 billion and employed over 350,000 people (Jameson et al., 1995). In Hawaii, coral reefs are central to a $US700 million and expanding marine recreation industry. Reef fish, lobsters, and bottom fish generate about $US20 million in landings annually and are an important source of food for local and restaurant consumption (Grigg, 1997). In Guam and the Northern Marianas, 90 percent of economic development is related to coastal tourism (NOAA, 1998). Between 1985 and 1995, visitor numbers on Guam rose from 300,000 to 1,300,000 per year and the hotel industry is now the single largest private sector employer on Guam. Diving brings $US148.6 million annually to Guam (Birkeland, 1997). Tourism to the Great Barrier Reef generates about $US1 billion (Done et al., 1996).

Diagnostic Biological Monitoring Is Essential To Manage Coral Reefs

Coral reef monitoring programs have become ubiquitous over the course of the past two decades (Risk, 1992; Eakin et al., 1997), ranging from monitoring by individual research scientists to that conducted by large institutions, also including regional networks such as the CARICOMP (Caribbean Coastal Marine Productivity) network (CARICOMP, 2000) and the Atlantic and Gulf Reef Assessment (AGRA) rapid assessment protocol (Steneck et al., 1997), and world-wide efforts such as the Global Coral Reef Monitoring Network (GCRMN, 2000). The scope of reef monitoring has recently expanded even further with the introduction of monitoring programs specifically designed for volunteer sport divers, such as the ReefBase Aquanaut, Reef Check and RECON programs (McManus et al., 1997; Reef Check, 2000; CMC, 2000). While these state of the art efforts have been very successful at what they were designed to do — document change in coral reefs — they have been for the most part, non-diagnostic; i.e., not capable of predicting what is causing the changes.

Because of the non-diagnostic nature of most coral reef monitoring programs, policy makers and government officials are not well equipped to communicate to the public or politicians trends in the condition of coral reef systems, the cause of coral reef resource decline, or the appropriate solution for remediation. To protect coral reef resources we should track the biological condition of these ecosystems the way we track local and national economies or diagnose personal health — using calibrated metrics — that integrate the influence of all forms of degradation caused by human actions and can thus help guide diagnostic, curative, restorative and preventive management actions.

Understanding Biological Attributes, Biological Condition, and Reference Condition Is Important In Diagnostic Monitoring

To build effective multimetric indexes it is critical to find the right attributes of a coral reef system to measure. Attributes that do not change in response to human impact tell nothing about the consequences of human activities for a particular coral reef location and its biota. Metrics must be selected based on whether they reflect specific and consistent biological responses to human activities. Ideal metrics should be relatively easy to measure and interpret. They should either increase or decrease predictably as human influence increases and should be sensitive to a range of biological stress (but in some cases can be response specific). Most important, metrics must be able to discriminate human-caused changes from natural variation (Karr and Chu, 1999).

Human activities degrade coral reefs by changing one or more of five principal groups of attributes (Table 2) often through undetected yet potentially devastating effects. Because properly-designed multimetric indexes are sensitive to these five factors, they quantify the biological effects of a broad array of human activities (Karr and Chu, 1999). The focus of a metric may be an indicator organism, many organisms, or in other cases it is not an organism at all, but some other biological attribute (i.e., nitrogen isotope ratios in macrophyte tissue).

The use of biological attributes has been justified in marine pollution monitoring programs focusing on chemical contamination for at least three reasons (Maher and Norris, 1990). First, they assess only those pollutants which are bioavailable, ostensibly those which are most important. Second, they can reveal biological effects at contaminant levels below current chemical analytical detection limits (either due to chronic, low level pollution or short-term pulses). Third, biological attributes can help assess synergistic or additive antagonistic relationships among pollutants, an important consideration with the typical combination of pollution impacts impinging on most reefs in the developing world (Ginsburg, 1994).

A far more important point and advantage of biological attributes is that they are useful in detecting human degradation caused by factors other than chemical contamination (Table 2).

The aim of any coral reef assessment program is to distinguish relevant biological signal from noise caused by natural spatial and temporal variation. Faced with the dizzying number of variables, disturbances, end-points, and processes, marine managers and researchers have periodically failed to choose those attributes that give the clearest signals of human impact. The world’s coral reefs have suffered as a result.

Table 2. Five attributes of coral reef resources altered by the cumulative effects of human activity (adapted from Karr and Chu, 1999), with examples of degradation from Montego Bay, Jamaica (Jameson and Williams, 2000).

Attribute	Components	Degradation in Montego Bay
Water quality	Temperature, turbidity, dissolved oxygen, salinity, organic and inorganic chemicals, heavy metals, toxic substances	Coral bleaching from increased temperature and bacteria. Fish kills from oxygen depletion. Algal blooms from increased nutrients. Coral mortality from sedimentation. Potential coral mortality from greenhouse gasses (CO_2 increases & pH changes).
Habitat structure	Substrate type, water depth and current speed, spatial and temporal complexity of physical habitat	Coral physical damage and mortality from anchors, divers, boats and fishing gear.
Flow regime	Water direction, volume, flow timing	Port construction with peninsula road causing flow changes, oxygen depletion, fish kills, coral mortality and changes in fish population dynamics.
Food (energy)	Type, amount and size of organic source particles entering reef, seasonal pattern of energy availability, light intensity	Light intensity reduced by sediment and sewage inputs.
Biotic interactions	Changes in competition and predation, stimulated by fishing, disease, parasitism, mutualism, and introduction of alien taxa	Sport and commercial fishing. Coral disease. Sea urchin die-off. Algal overgrowth of coral.

The biological condition of coral reef systems within a region is usually a continuum, varying from near pristine to severely degraded. To fully understand, rank, and evaluate those reefs, researchers should also measure biological condition on a continuous scale along this gradient (Ellis and Schneider 1997). Multimetric biological indexes furnish a yardstick for measuring, tracking, evaluating, and communicating continuous variation in biological condition. Instead of simply labeling a site "control" or "treatment", "impaired" or "unimpaired", "acceptable" or "unacceptable", a multimetric assessment identifies and preserves finer biological distinctions among sites, in the index itself and in the values of the component metrics. Dichotomous methods for evaluating biological condition lead to a variety of analytical and even regulatory problems. What is or is not an acceptable threshold in some biological (or chemical) metric depends on a site's context. Thresholds acceptable on a coral reef close to urban development may be totally unacceptable on a reef within a marine protected area. In addition, threshold definitions change over time as science and human values change, as people learn more, and as measurement techniques become more sophisticated.

Measuring biological condition with a continuous yardstick such as an IBI puts a site along a continuum of condition in comparison with other sites or other times, allowing thresholds to be reset according to context. It also permits a ranking of many sites — which might all be labeled "degraded" in a dichotomous scheme — so that priorities may be set for budget-constrained protection and restoration efforts.

Biological assessment must have a standard (reference condition) against which the conditions of one or more sites can be evaluated. In multimetric biological assessment, reference condition equates with biological integrity. IBIs measure the divergence from biological integrity. When divergence is detected, society has a choice: to accept divergence from integrity at that place and time, or to restore the site. There are few, if any, coral reefs remaining in the world that have not been influenced by human actions. Defining and selecting reference sites, and measuring conditions at those sites, requires a careful sampling and analysis plan.

A Continuing Review of Coral Reef Attributes

Jameson et al. (1998) review the status of biomonitoring using coral reef attributes. Appendix 1 includes new additions to this review. With few notable exceptions (Table 3), the majority of these attributes have not yet been fully developed into usable metrics (i.e., a metric for which a quantitative dose-response change in attribute value has been documented and confirmed across a gradient of human influence that is reliable, interpretable and not swamped by natural variation). Metrics should also be calibrated for the specific locations for which they are intended to be used in and metric values transformed into scores. In these respects, coral reef diagnostic monitoring lags far behind freshwater and temperate marine programs, many of which use metrics that have undergone extensive calibration and have been developed into multimetric indices of biotic integrity with well-defined interpretative frameworks (e.g., Karr et al., 1986; Lenat, 1988; Lang et al., 1989; Karr,1991; Rosenberg and Resh, 1993; Kerans and Karr, 1994; Wilson and Jeffrey, 1994; Davis and Simon, 1995; Karr and Chu, 1999; Simon, 1996). Many of these indexes result in the calculation of a simple numerical "score" for a particular site, which can then be compared over time or with other sites. Such rankings have an intuitive appeal to resource managers and users, and can be an effective means of galvanizing political willpower towards pollution prevention and conservation activities. Because the multimetric index is grounded in biological context and situation it can be expressed as a single number (IBI) or the metrics within the IBI can be expressed in a narrative that describes exactly how the biota at a site differs from what might be expected at a minimally disturbed site. The potential for diagnostic uses to identify causes of degradation is present as well.

Table 3. Coral reef metrics that show a quantitative change in attribute value across a gradient of human influence that is reliable and interpretable and that have been calibrated for specific locations.

Metric/ Impact	Parameters	Status	Reference/Location
Calibrated Numerical Coelobite Index/ Drilling discharges	Points assigned for presence - absence & abundance of certain important coelobite groups (i.e., *Homotrema rubrum*, other encrusting foraminifers, boring sponges, non-boring sponges, scyphozoans, bryozoans, molluscs, & serpulids). Points also given for the number of *H. rubrum* plus bryozoan colonies/ 100 cm^2.	Potential for monitoring sedimentation on coral is untested	Choi, 1982/ Pacific - Philippines
Gastropod Imposex - RPS Index/Tributyltin	Frequency of imposex (imposition of male sexual characteristics on female marine snails) in females and relative penis size	Fully developed	Ellis and Pattisina, 1990/Caribbean, Pacific, Indian
Nitrogen Isotope Ratios in Reef Organismal Tissues/Human sewage	Tissues of reef corals from sites with heavy human sewage inputs showed significantly higher $\delta^{15}N$ (ratio of $^{15}N/^{14}N$) values than coral tissues from relatively "clean" sites.	Calibrated for Indonesian and Jamaican coral reefs; further comparative work needed to test applicability to other geographic regions.	Risk et al., 1994; Dunn, 1995; Heikoop, 1997; Risk & Erdmann, 2000/Indonesia (Zanzibar, Maldives) Lapointe, 1999/Negril, Jamaica

Coral Damage Index/Coral physical damage	Sites are listed as “hot spots” if in a transect the percent of broken coral colonies is greater than or equal to 4% or if the percent cover of coral rubble is greater than or equal to 3%.	Fully developed	Jameson et al. 1999/Red Sea
FoRAM Protocol	The protocol consists of the following: sediment analysis, analysis of live larger foraminiferal assemblages, and *Amphistegina* foraminifera population analysis including abundance, presence of bleaching, and other evidence of specific stressors.	Further dose-response research using *Amphistegina* is in progress. Further comparative work needed to test applicability to other regions. Not transformed into an index.	Hallock, 2000/Florida Keys

Where Do We Go From Here?

Creating A Diagnostic Monitoring Program Using the Biocriteria Process

The first step toward effective diagnostic coral reef monitoring is to realize that the goal is to measure and evaluate the consequences of human actions on coral reef systems. The relevant measurement endpoint for coral reef monitoring is biological condition; detecting change in that endpoint, comparing the change with a minimally disturbed baseline condition, identifying the causes of the change, and communication of these findings to policymakers and citizens are the tasks of biological monitoring programs. Understanding and communicating the consequences of these human-induced ecosystem changes to all members of the human community is perhaps the greatest challenge of modern ecology (Karr and Chu, 1999).

The use of multiple measures, or metrics, to create indexes of biological integrity and biocriteria is a systematic process involving discrete steps. Jameson et al. (1998) and (Gibson et al., 1997) describe this process in detail and it is summarized in Table 4.

Table 4. Sequential progression of the biocriteria process.

Step 1	Preliminary classification of the coral reefs to determine reference conditions and regional ecological expectations - Coral reef classification - Determination of best representative sites (reference sites representative of class categories)
Step 2	Biological survey - Sampling along a gradient of conditions permits metric calibration and discrimination - Collection of data on biota and physical/chemical habitat - Compilation of raw data
Step 3	Final classification - Test preliminary classification - Revise if necessary
Step 4	Metric evaluation and index development - Data analysis (data summaries) - Testing and validation of metrics by coral reef class - Evaluation of metrics for effectiveness in detecting impairment - Aggregation of metrics into index - Selection of biological endpoints - Test the index for validity on another data set
Step 5	Biocriteria development - Adjustment by physical and chemical covariates - Adjustment by designated aquatic life use
Step 6	Implementation of monitoring and assessment program - Determination of temporal variability of reference sites - Identification of problems
Step 7	Protective and remedial management action - Initiate programs to preserve exceptional waters - Implement management practices to identify and address the causes of this degradation and to restore the biota of degraded waters
Step 8	Continual monitoring and periodic reviews of reference sites and biocriteria - Biological surveys continue to assess efficiency of management efforts

- Evaluate potential changes in reference condition and adjust biocriteria as management is accomplished

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Major Issues And Next Steps

Classifying Coral Reefs For Biological Monitoring

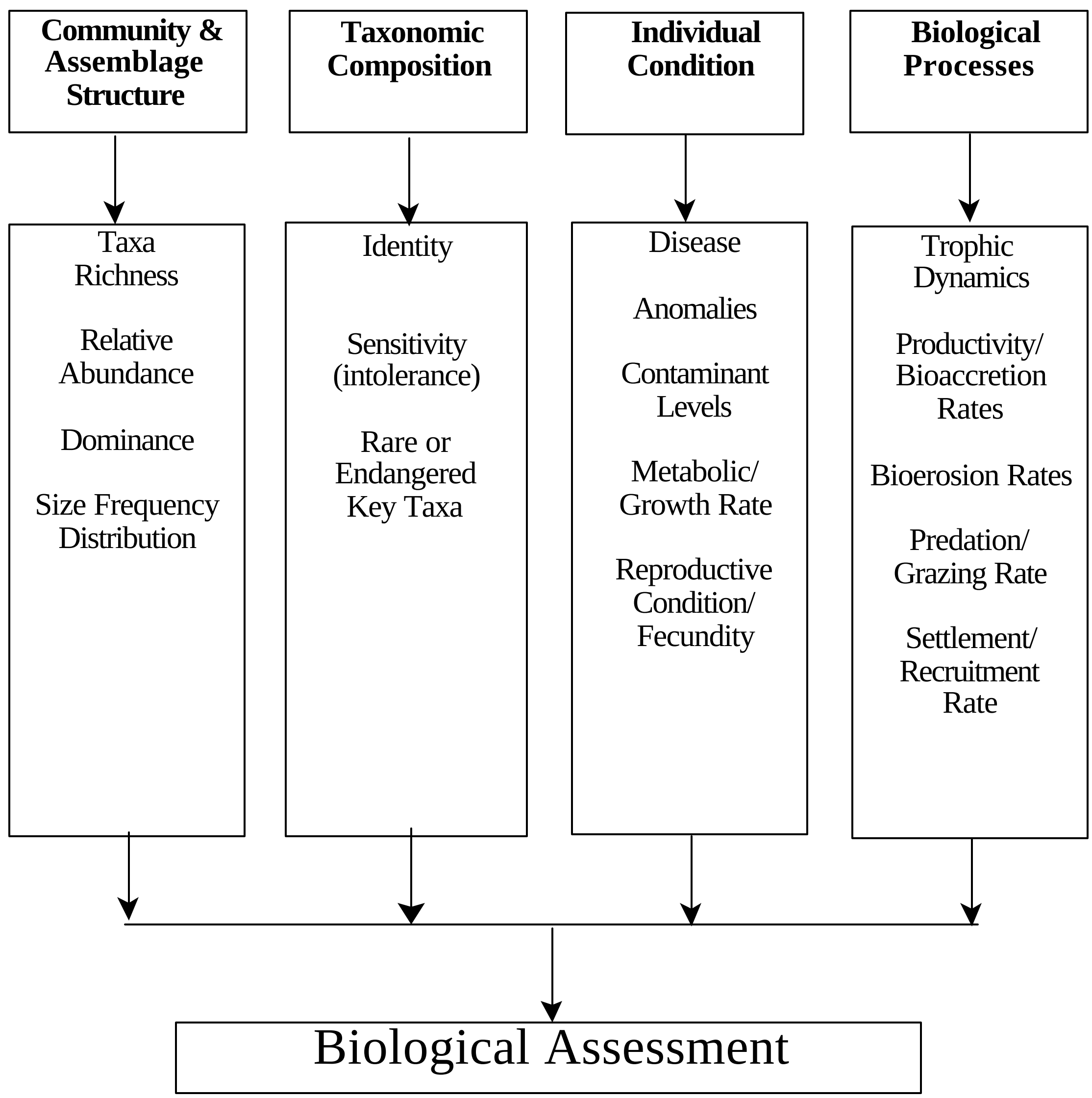
One of the most difficult challenges in creating IBIs and biological criteria for coral reefs is developing a workable classification system for natural systems that includes ecoregions (possibly subregions) and classes of sites (Jameson et al., 1998). The point of classification is to group coral reef natural systems by physical and biological community characteristics such that biotic responses are similar both in the absence of human disturbance and after human disturbance. Hypothetical examples of coral reef classes might be; windward central Pacific oceanic atolls, eastern Indonesian nearshore fringing reef slopes, or Caribbean lagoonal reefs. In some cases, these groupings may coincide with ecoregion boundaries; in others, they may cross those boundaries. To evaluate sites over time and place, we need groupings that will give reliable metrics and accurate criteria for scoring metrics to represent biological condition. The challenge is to create a system with only as many classes as are needed to represent the range of relevant biological variation in a region and the level appropriate for detecting and describing the biological effects of human activity in that place (Karr and Chu, 1999).

A coral reef classification system designed for diagnostic monitoring will be different than a classification system designed for the more traditional use of identifying conservation areas. Classification based on ecological dogma, on strictly chemical or physical criteria, or even on the logical biogeographical factors used to define ecoregions is not necessarily sufficient for biological monitoring. One must use the best natural history, biogeographic, and analytical resources available to choose a classification system (Karr and Chu, 1999). In freshwater streams, higher-level taxonomic and ecological structure usually provide better guidelines for classification than focusing primarily on species (Karr and Chu, 1999). In general, ecological organization and regional natural history are better guides for site classification and for signaling human disturbance than a focus on species composition. Once a coral reef classification system is proposed its usefulness must be tested using relevant metrics. The primary factors which make coral reefs biologically similar or different and that may be important in defining ecoregions and classes will be discussed in a future publication (Jameson et al. in prep.).

The Framework For The Definition Of Coral Reef Multimetric Indexes

Figure 1 shows the organizational structure of the types of attributes that should be incorporated into coral reef biological assessment. The framework is rooted in sound ecological principles and a similar version has been successful in freshwater bioassessment (Barbour et al., 1995). The use of each attribute is based on a hypothesis about the relationship between the coral reef condition and human influence. Multimetric indexes are generally dominated by metrics of taxa richness, because structural changes in aquatic systems, such as shifts among taxa, generally occur at lower levels of stress than do changes in ecosystem process (Karr and Chu, 1999). However, multimetric indexes also often include measures of ecological structure, frequency of diseased individuals, etc. and are broad in scope. Multimetric indexes can detect many influences in both time and space, reflecting changes in resident biological assemblages caused by single point sources, multiple point sources, and nonpoint sources. They can be useful in monitoring one coral reef or several, and they permit comparisons over a wide geographic area. The wide-ranging responsiveness of multimetric biological indexes makes them an ideal tool for judging the effectiveness of management decisions (Karr and Chu, 1999).

Figure 1. Framework showing the types of attributes that should be incorporated into coral reef biological assessment (adapted from Barbour et al., 1995).



Multimetric indexes avoid flawed or ambiguous indicators, such as diversity indexes or population size, and they are wider in scope (Karr and Chu, 1999). Diversity indexes are avoided because they combine richness and relative abundance; most IBIs, for example, include both richness and dominance metrics. Density or abundance measures are typically not used because of their high natural variation.

For a metric to be useful, it must be:

- Relevant to the biological community/assemblage under study and to the specified program objectives;

- Sensitive to recognized and unrecognized reef stressors;

- Able to provide a response that can be discriminated from natural variation;

- Environmentally benign to measure in the coral reef environment; and

- Cost-effective to sample.

Thus, metrics reflecting biological characteristics may be considered as appropriate in coral reef bioassessment and biocriteria programs if their relevance can be demonstrated, response range is verified and documented, and the potential for application in coral reef resource assessment programs exists. Tables 5-8 demonstrate that there is existing research that fits into every attribute within the coral reef bioassessment framework (Figure 1).

Table 5. Community and assemblage structure: An analysis of existing research in relation to the types of attributes that should be incorporated into coral reef indexes of biotic integrity.

Types of Attributes	Taxonomic Group or Specific Attributes	Representative References
Taxa Richness [1]	Scleractinian corals	Aronson et al., 1994 English et al., 1994
	Chaetodonts	Reese, 1981 & 1994 Crosby and Reese, 1996 Ohman et al., 1998
	Larval fish assemblages	Doherty, 1991
	Sessile reef assemblage	Alcolado et al., 1994
	Coelobites	Choi, 1982
	Stomatopod crustaceans	Erdmann and Caldwell, 1997 Steger and Caldwell, 1993
	Amphipods	Thomas, 1993
	Soft-bottom benthic assemblage structure	Bilyard, 1987 Gray and Mirza, 1979
Relative Abundance[2]	Commercial fish/invertebrate species	Reef Check, 2000
and Dominance[3]	Macrophytic algal blooms	McManus et al., 1997
	Heterotrophic macroinvertebrates	Dustan and Halas, 1987 Risk et al., 1994
	Internal bioeroders	Risk et al., 1995 Holmes, 1997 Holmes et al., 2000
	Corallivores	Birkeland and Lucas, 1990
	Foraminifera	Hallock, 1996 Cockey et al., 1996 Hallock, 2000
	Soft-bottom benthic assemblage structure	Pearson and Rosenberg, 1978

	Coral morphology triangles	Edinger and Risk, 1999
Size Frequency Distribution [4]	Coral population colony size structure	Bak and Meesters, 1998
	Stomatopod population size frequency	Erdmann and Sisovann, 1999

[1] Taxa richness is measured as number of distinct taxa and represents the diversity within a sample. Taxa richness usually consists of species level identifications but can also be evaluated as designated groupings of taxa, often as higher taxonomic groups (i.e., genera, families, orders, etc.) in assessment of invertebrate assemblages.
[2] Relative abundance of taxa refers to the number of individuals of one taxon as compared to that of the whole assemblage. The proportional representation of taxa is a surrogate measure for assemblage balance that can relate to both enrichment and contaminant problems.
[3] Dominance, measured as percent composition of dominant taxon or dominants-in-common, is an indicator of assemblage balance or lack thereof. It is an important indicator when the most sensitive taxa are eliminated from the assemblages and/or the food source is altered, thus allowing the more tolerant taxa to become dominant.
[4] Size frequency distributions describe the percentage of individuals in a population or assemblage that fall within defined size categories. Skew of these distributions from known baseline distributions can be a sensitive indicator (e.g., indicate occurrence of past pulse disturbance that eliminated all adults, etc.)

Table 6. Taxonomic Composition: An analysis of existing research in relation to the types of attributes that should be incorporated into coral reef indexes of biotic integrity.

Types of Attributes	Taxonomic Group or Specific Attributes	Representative References
Identity[1]	Reef Check key taxa of regional ecological importance	Hodgson, 1999
Sensitivity[2]	Larval fish assemblages	Doherty, 1991
(intolerance)	Amphipods	Thomas, 1993
	Foraminifera	Hirschfield et al., 1968 Hallock, 1996 Cockey et al., 1996 Hallock, 2000
	Stomatopod crustaceans	Erdmann and Caldwell, 1997
Rare or Endangered Key Taxa[3]	Commercially valuable fish/invertebrate species	Reef Check, 2000 McManus et al., 1997

[1] Identity is knowledge of individual taxa and associated ecological patterns and environmental requirements. Key taxa (i.e., those that are of special interest or ecologically important) provide information that is important to the condition of the target assemblage. The presence of alien or nuisance species may be an important aspect of biotic interactions that relates to both identity and sensitivity.
[2] Sensitivity refers to numbers of pollutant-tolerant and -intolerant species in the sample.
[3] Recognition of those taxa considered to be threatened or endangered provides additional legal support for remediation activities or recommendations.

Table 7. Individual Condition[1]: An analysis of existing research in relation to the types of attributes that should be incorporated into coral reef indexes of biotic integrity.

Types of Attributes	Attributes	Representative References
Disease	Coral vitality/mortality indices	Dustan, 1994 Gomez et al., 1994 Ginsburg et al., 1996
	Zooxanthellae loss in corals	Jones, 1997
	Coral diseases	Richardson, 1996 Santavy and Peters, 1997 Rosenberg & Loya, 1999
Anomalies	Physical damage to corals	Dixon et al., 1993 Chadwick-Furman, 1996 Hawkins & Roberts, 1997 Jameson et al., 1999
	Ectoparasites on reef fishes	Evans et al., 1995
	Developmental defects in reef fishes	Lisa Kerr, University of Maryland, Baltimore, USA, pers. comm.
	Gastropod imposex	Ellis and Pattisina, 1990 Gibbs and Bryan, 1994
	Coral fertilization rate	Harrison and Ward, in review
	Expression of stress-induced genes in corals	Snell, in progress
	Molecular biomarkers in corals	Downs et al., in press
Contaminant Levels	Depth charge chemicals in damselfish	Jameson, 1975
	Amphipod burrowing behavior	Oakden et al., 1984
	Bioaccumulation of metals, phosphorus in coral skeletons	Dodge et al., 1984 Hanna and Muir, 1990
	Metal bioaccumulation in macrophytes	Brown and Holly, 1982

	Bioaccumulation in molluscs	Goldberg et al., 1978
	Bioaccumulation in sponges	D. L. Santavy, U.S. EPA Office of Research and Development, Gulf Ecology Division, pers. comm.
	Nitrogen isotope ratios in coral skeletons, stomatopod tissues	Risk et al., 1994 Heikoop et al., 2000 Risk and Erdmann, 2000
Metabolic/Growth Rate	Coral growth rate	Brown, 1988 Edinger et al., 2000
	Chaetodont territory size, antagonistic encounter rate	Hourigan et al., 1988 Crosby and Reese, 1996
	Giant clam shell growth rate	Ambariyanto and Hoegh-Guldberg, 1997 Belda et al., 1993a
Reproductive Condition/ Fecundity	Coral fecundity and fertilization rates	Richmond, 1994; 1996 Ward and Harrison, in press Harrison and Ward, in review

[1] Individual condition metrics generally focus on chronic exposure to chemical contamination. The condition of individuals can be rated by observation of either physical (morphological), chemical, or behavioral characteristics. For example, physical characteristics of individuals that may be useful for assessing chemical contaminants include those that result from microbial or viral infection and teratogenic or carcinogenic effects during development of that individual. Metrics of this nature have been implemented successfully in freshwater fish multimetric indexes (e.g., % diseased individuals). The underlying concept of the individual condition approach in biomonitoring is that contaminant effects occur at the lower levels of biological organization (i.e., at the genetic, cell, and tissue level within individual organisms) before more severe disturbances are manifested at the population or ecosystem level. Individual condition metrics may provide a valuable complement to ecological metrics if they are of pollutant-specific nature, responsive to sublethal effects, and the time and financial costs for the measurement are consistent with available resources.

Table 8. Biological Processes: An analysis of existing research in relation to the types of attributes that should be incorporated into coral reef indexes of biotic integrity.

Types of Attributes	Attributes	Representative References
Trophic Dynamics	Benthic shift to heterotrophic macroinvertebrates	Birkeland, 1987 Hallock, 1988 Risk et al., 1994 Tomascik et al., 1994
	Foraminifera shift to taxa lacking algal symbionts	Cockey et al., 1996 Hirschfield et al., 1968 Hallock, 2000
Productivity/ Bioaccretion Rates	Whole reef productivity/ calcification profiles	Barnes, 1983 Chalker et al. 1985
Predation/Grazing Rate	Human predation on reef fish	Smith-Vaniz et al., 1995
	Changes in sea urchin predation rates	McClanahan, 1988 McClanahan and Muthiga 1989 McClanahan and Mutere, 1994
Settlement/Recruit ment Rate	Coral recruitment	Tomasick, 1991 Hunte and Wittenberg, 1992 Richmond, 1994; 1996 Ward and Harrison, 1997
	Crustacean recruitment (stomatopods, lobster)	Herrnkind et al., 1988 Erdmann and Caldwell, 1997 Steger and Caldwell, 1993 ENCORE team, in review
	Gastropod recruitment	Garrity and Levings, 1990

A Research Strategy For Creating Coral Reef IBIs

The following research strategy should help focus policy makers and the scientific community on filling the research and information gaps necessary to develop multimetric indexes for coral reef assessment.

The approach of using IBIs and biological criteria for coral reef assessment is unique and different from previous coral reef monitoring and assessment efforts in the following ways.

- Coral reefs are classified so comparisons between similar environments can be made. If metrics are correctly calibrated and scored, it is also possible to compare across classes of reefs (i.e., the resultant IBI is directly comparable despite coming from different types of reefs).

- Minimally disturbed sites are used as reference sites from which to compare monitoring sites.

- Only metrics are used that show a quantitative dose-response change in attribute value that is documented and confirmed across a gradient of human influence that is reliable, interpretable and not swamped by natural variation.

- IBIs are designed to provide a unique early warning characteristic.

Well constructed multimetric indexes typically examine two or more assemblages because different organism groups react differently to perturbation (Table 9). The more diverse the measures used, the more robust the investigative techniques and the more confidence the manager can place in the results. However, this idea must be reconciled with the limitations of the costs of multiple and diverse surveys and the relative availability of reliable scientific methods to measure some assemblages. The most promising approaches will likely be measures of sessile epibenthos, benthic macroinvertebrates, fish, macrophytes, phytoplankton, and zooplankton (Gibson et al., 1997).

Table 9. Types of metrics, suggested number of metrics of each type, and corresponding levels in the biological hierarchy. Well-constructed multimetric indexes contain the suggested number of metrics from each type and therefore reflect multiple dimensions of biological systems (Karr and Chu, 1999).

Metric type	Number	Individual	Population	Community	Ecosystem	Landscape
Taxa richness	3-5	X	X	X	X	
Tolerance-intolerance	2-3		X	X		
Trophic structure	2-4			X	X	X
Individual health	1-2	X				
Other ecological attributes	2-3	X	X	X	X	X

The actual sampling regimes that will be used to measure the attributes listed in the research strategies are critical and require development. One of the biggest challenges will undoubtedly come from trying to get diverse people to agree on a standard sampling regime. The tendency to argue for favorites should be replaced by a systematic effort to define the kind and amount of sampling that is necessary to reliably detect differences among sites. For each IBI, one needs to devise the techniques used to sample the various organisms and to define which organisms are most important to sample (i.e., which organisms give sampling efficiency and a robustness to the results that gives confidence in the resulting inferences). Because results will be compared in time and space it is crucial that standard methods be developed and tested. Another crucial step will be the use of an analytical framework that gives clear results, and that extracts the most relevant and important insights from the data collected. Oftentimes that requires all of us to think outside the boxes that we are used to thinking in.

Key components of sampling design and analysis include sampling across the full range of biological condition from minimally influenced by human action to severely degraded. Care should be taken to avoid mixing different environment types. Sampling and analysis should focus on finding differences across that range of places without getting bogged down in the other sources of variation that are real but irrelevant (e.g., seasonal changes don't have to all be documented and understood; one does not have to have sampled every microhabitat within the system; one does not have to know how every sampling gear and protocol works; all resident species do not have to be recorded). At the same time, one has to work carefully to define the number of samples necessary to make robust inferences about the condition of places (to be sure that we don't have an excess of data or too few data). In our experience, biologists claim to need far more data than they actually need and then they tend not to look at the things that are most relevant to find patterns that are clearly related to the gradient of human influence/biological condition.

The mixing of sampling methods (e.g., transects and quadrats) is another challenge, in places like coral reefs, that are hard to sample with a standard single method. Early work on stream invertebrates hoped to capture all taxa in all microhabitats but the creation of such composite samples often created difficulties in data interpretation (Parsons and Norris 1996) while samples from single habitats were adequate to access the condition of sites (Kerans et al., 1992). The best approach for coral reef ecosystems can only be defined by systematic study and evaluation of the level of sampling necessary to provide high quality and easily interpreted data.

All sampling methods need to have precise sample effort rules (even if a multiple sampling approach is required, each should be based on a standardized sample effort). When that is done, it is possible to evaluate the best possible way to express biological results (e.g., absolute abundance, relative abundance, taxa richness) as well as to define the best components of biology to be used (e.g., predator taxa richness, omnivore relative abundance, etc.).

Our recommendation is to limit the number of sampling methods (even though we know much information is not being captured) to foster development of standard methods and to limit the time and costs of sampling efforts to the minimum necessary to provide reliable and easily interpreted results. Neither all microenvironments nor all taxa prsent need to be included in standard sample efforts. Furthermore, for sampling programs to be used by diverse agencies and organizations, sampling costs must be controlled. The more efficient and cost effective the sampling at a site the more groups can afford to participate and the more sites that can be sampled. An example of this type of approach would be a benthic cryptofauna IBI whereby a robust quadrat sampling technique would be used to sample all the rubble dwellers in 1 meter square quadrats placed upon reef flats (relatively much easier to sample microhabitats that are usually quite homogenous and whereby the ethical issues of destroying live coral are avoided). This type of sampling technique would allow sampling of the majority of the most promising indicator taxa, including stomatopods, amphipods, forams, boring sponges, boring bivalves, crabs, upogobeiid shrimps and other crustaceans, select species of echinoderms, many polychaetes and platyhelminths, etc. This would be an objective sampling technique, low tech, easily done even snorkeling (without scuba), and would generate data that reflects both species composition and abundances of the organisms present in the sampled environment.

In the research strategies, we focus primarily on relative abundance and taxa richness rather than absolute abundance metrics. Past experience in fresh and marine waters showed that relative abundance metrics worked best because of the often large shifts in absolute abundances in species and their often patchy distributions (also single species have not been found to be very good indicators in fresh water situations) (J. R. Karr, personal observation). In the research strategies we include a few abundance attributes (in the spirit of keeping an open but cautious mind) in the endangered species category, but predict that the taxa richness and relative abundance measures will most likely yield the strongest signals. One problem with an endangered species (as a single species) focus is that their ranges are often limited and thus the signal from that may not be very widely applicable.

Tables 10-15 outline research priorities for creating coral reef IBIs. These tables use the framework in Figure 1 to define the types of attributes, build upon existing coral reef research and draw from the successes of other freshwater and marine IBIs (Karr and Chu 1999, Gibson et al., 1997, Davis and Simon 1995, Simon, 1996). Other attributes that have not been explored are also included in the tables as potential research subjects. These tables are provided as a starting point and are not intended to preclude ideas for other new metrics that may be appropriate for coral reef IBIs.

In freshwater environments:

Total taxa richness (total number of taxa present in a sample),

- Richness of particular taxa or ecological groups,
- Taxa richness of intolerant organisms,
- Relative abundance of stress tolerant taxa (% of all sampled individuals),
- Trophic organization, e.g., relative abundance of predators or omnivores, and
- Relative abundance of individuals with deformaties, disease, lesions or tumors

have been consistently reliable (i.e., show change over a gradient of human-induced degradation) regardless of taxon used or habitat sampled (Karr and Chu 1999) and are used as a starting point for Tables 10-15.

The Importance of Understanding Tolerant and Intolerant Coral Reef Taxa

Indicator taxa are those organisms whose presence (or absence) at a site indicates specific environmental conditions. If an organism known to be intolerant of pollution is found to be abundant at a site, high water quality conditions can be inferred. On the other hand, dominance by pollution tolerant organisms implies a degraded condition. When available, indicator taxa are an important, cost-effective preliminary survey tool for site assessments.

A comprehensive review of coral reef intolerant taxa was conducted by Jameson et al. (1998). Thomas (1993) reviews the use of amphipods and Erdmann and Caldwell (1997) review the use of stomatopods in coral reef monitoring situations. Hallock (2000) outlines the intolerant features of foraminifera and will develop a compact disc on the FORAM protocol for use in low tech settings. In temperate marine waters, Swartz et al. (1985; 1986; 1994) demonstrated the sensitivity of the amphipod *Rhepoxynius abronius* to the complex contaminant mixture along pollution gradients from the Los Angeles County Sanitation Districts' sewage outfalls. Other studies performed by Swartz et al. (1994) at a designated Superfund site in San Francisco Bay showed that acute sediment toxicity lab tests of *R. abronius* reliably predicted biologically adverse sediment contamination in the field.

A well-known indicator for degraded systems is the polychaete *Capitella capitata. C. capitata* and its related species are collectively known as the C. *capitata* complex. In general, the presence of this tolerant taxon corresponds to a dominance of deposit feeders that colonize an area as organic pollution increases. Swartz et al. (1985) observed dominance of *Capitella* near sewage outfalls. A recent study in the MidAtlantic Bight by the U.S. Army Corps of Engineers (1996) suggests that the polychaete *Amastigos caperatus* may have indicator potential similar to the *Capitella* complex.

The challenge in using pollution tolerant indicator organisms is that some of these organisms may be ubiquitous and found in naturally occurring organically enriched habitats as well as in minimally disturbed waters. To be useful as an indicator, they must have displaced other, less robust taxa and have achieved numeric dominance. An example of this dilemma is the use of the protozoan genus *Acanthamoeba* as a sewage indicator. Because the animal is capable of encysting, it is present as a public health indicator in sediments long after less durable indicator groups such as the coliform and pseudomonas groups have perished. This same longevity, however, argues against use of the organism as an indicator in open waters because it can be found distributed in sediments far away from the original source of sewage pollution and long after the plume has dispersed (Gibson et al., 1997).

The best option may be the paired use of both pollution tolerant and intolerant indicator organisms. If both indicators change concurrently in opposite directions, more confidence can be placed in the interpretation. When indicator species are employed in tandem for impact investigations, a gradient of species distribution can often be identified. Such a gradient might progress from the most degraded waters, having low diversity communities dominated by pollution tolerant opportunistic species, to undisturbed or minimally disturbed waters having diverse communities comprised of a wide range of taxa, including pollution sensitive ones and some that are pollution tolerant.

Much work needs to be done to understand the tolerance and intolerance of coral reef invertebrates, fishes and plants to specific human activities and mixes of human activities. Once obtained, this understanding will provide useful diagnostic tools to coral reef managers and result in the acquisition of management information and not just the collection of monitoring data.

Sessile Epibenthos Research Strategy

Research priorities for creating a coral reef sessile epibenthos IBI are outlined in Table 10. Most coral reef monitoring programs in existence today are focused on sessile epibenthos (hard and soft corals, sponges, etc). Consequently, a large body of data has been assimilated for this assemblage in tropical seas around the world. Examination of epibenthic assemblage structure and function is a valuable tool for evaluating the condition of benthic habitats, for monitoring rates of recovery after environmental perturbations and potentially to provide an early warning of developing impacts to the system - and has been tested with considerable success in Washington, North Carolina, and Florida (Gibson et al., 1997).

Some specific advantages of monitoring sessile epibenthos to determine overall assemblage health include:

- Sessile epibenthos cannot avoid ambient exposure and typically accumulate indicative pathogens and toxicants, while the epibenthic assemblage composition reflects the average salinity, temperature and dissolved oxygen of that locale over an extended period of time. (Day et al., 1989).

- Sessile epibenthos include the primary habitat structuring taxa of coral reefs - clearly an important group to monitor when considering coral reef health.

- Many state and federal monitoring programs already monitor coral reef sessile epibenthos and have the necessary in-house expertise. Thus, it has extensive historical and geographic application.

Some limitations of sessile epibenthic sampling include (Gibson et al., 1997):

- The condition of benthic habitats can vary over relatively small scales. Therefore, if too few samples are collected from a specified area, the ambient heterogeneity to be expected may be missed, potentially leading to incorrect conclusions regarding the biological and water quality conditions in the area.

- Sessile epibenthos are very sensitive to substrate type.

- The cost and effort to identify and count sessile epibenthos samples/transects can be significant, requiring tradeoffs between expense and the desired level of taxonomic resolution and confidence in decisions based upon the collected data. Ferraro et al. (1989) have developed a power-cost efficiency (PCE) analysis to address this problem. Doberstein et al. (in press) demonstrate the compromises associated with subsampling (or counting) too few organisms as recommended in some protocols.

Table 10. Research priorities for creating a coral reef sessile epibenthos index of biotic integrity (IBI). Percent sign (%) denotes relative abundance (number of individuals of one taxa as compared to that of the whole assemblage). Cumulative = cumulative human-induced disturbance (i.e., a combination of factors that could include (but is not limited to) fishing, physical damage, increased temperature and turbidity, chemical contaminants, sedimentation, altered flow regimes, pesticides, nutrients, metals, sediments, and/or bacteria. To reach metric status attributes need the following research: 1 = a quantitative dose-response change in attribute value documented and confirmed across a gradient of human influence that is reliable, interpretable and not swamped by natural variation; 2 = calibration for specific region/location; 3 = transformation. In addition, the entire IBI needs index development (an interpretive framework) that will result in the calculation of a simple numerical score for a particular site, which can then be compared over time or with other similar sites. Most attributes can be applied to all tropical seas.

Organizing Structure Attributes	Hypothetical Response Specificity	Hypothetical Response	Research Needs
Community & Assemblage Structure			
Taxa richness			
Total taxa richness (number of taxa/sample)	Cumulative	Decrease	1, 2, 3
Total hard coral taxa richness	Cumulative	Decrease	1, 2, 3
Total sponge taxa richness	Cumulative	Decrease	1, 2, 3
Total soft coral taxa richness	Cumulative	Decrease	1, 2, 3
Total tunicate taxa richness	Cumulative	Decrease	1, 2, 3
Dominance/Relative Abundance			
% dominant taxa	Cumulative	Increase	1, 2, 3
% soft corals	Cumulative	Increase	1, 2, 3
% zoanthids	Cumulative	Increase	1, 2, 3
% corallimorpharians	Cumulative	Increase	1, 2, 3
Size Frequency Distribution			
Hard coral colony modal size	Cumulative	Increase	1, 2, 3
Taxonomic Composition			
Sensitivity (tolerants and intolerants)			
Number of intolerant taxa [1]	Cumulative	Decrease	1, 2, 3
% tolerant taxa [2]	Cumulative	Increase	1, 2, 3
Number of sediment-intolerant taxa [3]	Sediment	Decrease	1, 2, 3
% sediment-tolerant taxa [4]	Sediment	Increase	1, 2, 3

Individual Condition			
Disease			
% corals w/disease/lesions/tumors	Cumulative	Increase	1, 2, 3
% gorgonians w/disease/lesions/tumors	Cumulative	Increase	1, 2, 3
% coral skeleton bioeroded/invaded	Nutrients	Increase	1, 2, 3
Anomalies			
Coral damage index	Anchor/diver	Increase	3
Expression of stress-induced genes in corals	Cumulative	Increase	1, 2, 3
Contaminant levels			
Nitrogen isotope ratios [5]	Fecal waste	Increase	2, 3
Coprostanol concentrations [6]	Fecal waste	Increase	2, 3
Bioaccumulation in hard corals	Cumulative	Increase	2, 3
Bioaccumulation in sponges	Cumulative	Increase	1, 2, 3
Metabolic/Growth rate			
Hard coral growth rates	Cumulative	Decrease	1, 2, 3
Reproductive Condition/Fecundity			
Hard coral fecundity & fertilization rates	Nutrients	Decrease	2, 3
Hard coral reproductive synchronization	Cumulative	Decrease	2, 3
Biological Processes			
Trophic dynamics			
% autotrophic sessile benthos	Sediments	Decrease	1, 2, 3
% heterotrophic sessile benthos	Cumulative	Increase	1, 2, 3
Productivity			
Productivity & calcification of coral reefs	Cumulative	Decrease	1, 2, 3
Settlement/Recruitment rate			
Hard coral settlement rate	Nutrients	Decrease	2, 3
Hard coral recruitment rate	Cumulative	Decrease	1, 2, 3

Potential candidates include, but are not limited to:

[1] certain hard and soft corals.

[2] certain hard corals, internal bioeroders (clionid sponges), certain filter feeders (sponges, hydroids).

[3] certain hard coral species, certain coelobites (bryozoans, tunicates)
[4] heterotrophic macroinvertebrates (sponges, barnacles), internal bioeroders (clionid sponges)
[5, 6] hard corals

Benthic Macroinvertebrate Research Strategy

Research priorities for creating a coral reef benthic macroinvertebrate IBI are outlined in Table 11. Benthic macroinvertebrates have a long history of use in freshwater and temperate marine biomonitoring programs, and much of this experience should be readily adaptable for use in coral reef environments.

Some particular advantages of using this assemblage are as follows:

- Relative ease of identification because taxonomic lists of local crustaceans, molluscs, and echinoderms can be fairly easily compiled.

- Sampling is as inexpensive as fish surveys, and can often be done with the same or similar equipment during the same survey.

- Decapod crustacea are usually very important prey for fish and are important components in benthic food webs. Some (e.g., shrimp and crabs) are harvested for human consumption.

Possible difficulties include the following (Gibson et al., 1997).

- There is greater potential for avoidance by organisms than when sampling for sessile epibenthos, though not as great as with fish surveys.

- Sensitivity to pollutants remains to be determined in many areas.

Table 11. Research priorities for creating a coral reef benthic macroinvertebrate index of biological integrity (IBI). Percent sign (%) denotes relative abundance (number of individuals of one taxa as compared to that of the whole assemblage). Cumulative = cumulative human-induced disturbance (i.e., a combination of factors that could include (but is not limited to) fishing, increased temperature and turbidity, chemical contaminants, sedimentation, altered flow regimes, pesticides, nutrients, metals, sediments, and/or bacteria. To reach metric status attributes need the following research: 1 = a quantitative dose-response change in attribute value documented and confirmed across a gradient of human influence that is reliable, interpretable and not swamped by natural variation; 2 = calibration for specific region/location; 3 = transformation. In addition, the entire IBI needs index development (an interpretive framework) that will result in the calculation of a simple numerical score for a particular site, which can then be compared over time or with other similar sites. Most attributes can be applied to all tropical seas, except those involving giant clams, which are not applicable to the Caribbean, South Atlantic and Gulf of Mexico.

Organizing Structure Attributes	Hypothetical Response Specificity	Hypothetical Response	Research Needs
Community & Assemblage Structure			
Taxa richness			
Total taxa richness (number of taxa/sample)	Cumulative	Decrease	1, 2, 3
Total stomatopod taxa richness	Cumulative	Decrease	2, 3
Total amphipod taxa richness	Cumulative	Decrease	2, 3
Total decapod taxa richness	Cumulative	Decrease	1, 2, 3
Total gastropod taxa richness	Cumulative	Decrease	1, 2, 3
Total bivalve taxa richness	Cumulative	Decrease	1, 2, 3
Total polychaete taxa richness	Cumulative	Increase	1, 2, 3
Total oligochaete taxa richness	Cumulative	Increase	1, 2, 3
Total echinoid taxa richness	Cumulative	Decrease	1, 2, 3
Total holothurian taxa richness	Cumulative	Decrease	1, 2, 3
Total crinoid taxa richness	Cumulative	Decrease	1, 2, 3
Dominance/Relative abundance			
% dominant taxa	Cumulative	Increase	1, 2, 3
% of bivalves that are bioeroding	Nutrients	Increase	1, 2, 3
Size frequency distribution			
Stomatopod modal size	Cumulative	Decrease	1, 2, 3

Taxonomic Composition			
Sensitivity (tolerants and intolerants)			
Number of intolerant taxa [1]	Cumulative	Decrease	1, 2, 3
% tolerant taxa [2]	Cumulative	Increase	1, 2, 3
Number of sediment-intolerant taxa [3]	Sediment	Decrease	1, 2, 3
% sediment-tolerant taxa [4]	Sediment	Increase	1, 2, 3
Rare or Endangered Key Taxa			
Number of large gastropods	Fishing	Decrease	2, 3
Number of lobster	Fishing	Decrease	2, 3
Number of holothurians	Fishing	Decrease	2, 3
Individual Condition			
Anomalies			
Amphipod burrowing	Cumulative	Decrease	1, 2, 3
Gastropod imposex	Tributyltin	Increase	1, 2, 3
Giant clam zooxanthellae size	Nutrients	Decrease	2, 3
Foraminifera (*Amphistegina*) analysis of stress symptoms: mottling, lack of symbiotic algae	Nutrients	Increase	2, 3
Contaminant levels			
Nitrogen isotope ratios in tissues[5]	Sewage	Increase	1, 2, 3
Coprostanol concentrations[6]	Sewage	Increase	1, 2, 3
Bioaccumulation in bivalves	Metals	Increase	2, 3
Metabolic/Growth rate			
Giant clam shell growth rate	Nutrients	Increase	2, 3
Mean weight per individual polychaete	Cumulative	Decrease	1, 2, 3
Mean weight per individual bivalve	Cumulative	Decrease	1, 2, 3
Reproductive Condition/Fecundity			
Fecundity[7]	Cumulative	Decrease	1, 2, 3
Biological Processes			
Trophic Dynamics			
% predators	Cumulative	Decrease	1, 2, 3
% omnivores	Cumulative	Increase	1, 2, 3

% corallivores	Cumulative	Increase	1, 2, 3
% filter feeders	Nutrients	Increase	1, 2, 3
% deposit feeders	Cumulative	Increase	1, 2, 3
% autotrophic foraminifera	Nutrients	Decrease	1, 2, 3
Settlement/recruitment rate			
Recruitment rate[8]	Cumulative	Decrease	2, 3

[1, 3] potential candidates include: stomatopods, amphipods, decapods, gastropods
[2, 4] potential candidates include: heterotrophic macroinvertebrates (zoanthids, echinoids, holothurians, crinoids), polychaetes/oligochaetes, certain sea urchin species
[5, 6, 7, 8] potential candidates include: stomatopods, other reef crustaceans, giant clams, other molluscs.

Fish Research Strategy

Research priorities for creating a coral reef fish index of biological integrity are outlined in Table 12. Fish are an important component of marine communities because of their economic, recreational, aesthetic and ecological roles. The abundance and health of the fish assemblage is also the primary indicator used by the public to discern the health of a water body .

Gibson et al. (1997) and Simon (1999) list the following characteristics of fishes that make them desirable components of bioassessment and monitoring programs.

- They are sensitive to certain habitat disturbances.

- Being mobile, sensitive fish species may avoid stressful environments, leading to measurable population patterns reflecting that stress (ex., abundances become inversely related spatially to the intensity of the disturbance).

- Fish are important in the linkage between benthic and pelagic food webs, making them useful in assessing macrohabitat differences.

- They are good indicators of long-term and current water quality, as they are long-lived (3-10+ years) and assimilate chemical, physical and biological degradation.

- They may also be easier and more cost effectively measured than other components of the biotic community (i.e., sampling frequency for trend assessment is less than for short lived organisms and the taxonomy is well established allowing professionals the ability to reduce laboratory time by identifying many specimens in the field).

The limitations on the use of fish in assemblage bioassessments include (Gibson et al., 1997):

- Some fish are very habitat selective and their habitats may not be easily sampled (e.g. reef-dwelling species in caves or coral formations).

- Marine and reef fish have been known to avoid stressful environments, reducing their exposure to toxic or other harmful conditions (K. W. Potts; M. V. Erdmann, personal observations)

Table 12. Research priorities for creating a coral reef fish index of biological integrity. Percent sign (%) denotes relative abundance (number of individuals of one taxa as compared to that of the whole assemblage). Cumulative = cumulative human-induced disturbance (i.e., a combination of factors that could include (but is not limited to) fishing, increased temperature and turbidity, chemical contaminants, sedimentation, altered flow regimes, pesticides, nutrients, metals, sediments, and/or bacteria. To reach metric status attributes need the following research: 1 = a quantitative dose-response change in attribute value documented and confirmed across a gradient of human influence that is reliable, interpretable and not swamped by natural variation; 2 = calibration for specific region/location; 3 = transformation. In addition, the entire IBI needs index development (an interpretive framework) that will result in the calculation of a simple numerical score for a particular site, which can then be compared over time or with other similar sites. Most attributes can be applied to all tropical seas.

Organizing Structure Attributes	Hypothetical Response Specificity	Hypothetical Response	Research Needs
Community & Assemblage Structure			
Taxa richness			
Total taxa richness (number of taxa/sample)	Cumulative	Decrease	1, 2, 3
Total native taxa richness[1]	Cumulative	Decrease	1, 2, 3
Total scarid taxa richness	Cumulative	Decrease	1, 2, 3
Total balistid taxa richness	Cumulative	Decrease	1, 2, 3
Total lutjanid taxa richness	Cumulative	Decrease	1, 2, 3
Total serranid taxa richness	Cumulative	Decrease	1, 2, 3
Total chaetodontid taxa richness	Cumulative	Decrease	1, 2, 3
Total acanthurid taxa richness	Cumulative	Decrease	1, 2, 3
Total haemulid taxa richness	Cumulative	Decrease	1, 2, 3
Total pomacanthid taxa richness	Cumulative	Decrease	1, 2, 3
Total pomacentrid taxa richness	Cumulative	Decrease	1, 2, 3
Total carangid taxa richness	Cumulative	Decrease	1, 2, 3
Total shark taxa richness	Cumulative	Decrease	1, 2, 3
Taxonomic Composition			
Identity			
Number of alien individuals	Cumulative	Increase	1, 2, 3
% alien taxa	Cumulative	Increase	1, 2, 3
Sensitivity (tolerants and intolerants)			
Number of intolerant taxa[2]	Cumulative	Decrease	1, 2, 3

% tolerant taxa[3]	Cumulative	Increase	1, 2, 3
Rare or Endangered Key Taxa			
% scarids	Fishing	Decrease	1, 2, 3
% lutjanids	Fishing	Decrease	1, 2, 3
% serranids	Fishing	Decrease	1, 2, 3
% sharks	Fishing	Decrease	1, 2, 3
Number of *Cheilinus undulatus*	Fishing	Decrease	1, 2, 3
Number of key aquarium species	Collecting	Decrease	1, 2, 3
Individual Condition			
Disease			
% w/disease/fin erosion/lesions/tumors	Cumulative	Increase	1, 2, 3
% w/ectoparasites	Cumulative	Increase	1, 2, 3
Anomalies			
% w/developmental defects	PCB's	Increase	1, 2, 3
Reproductive Condition/Fecundity			
Fecundity[2]	Cumulative	Decrease	1, 2, 3
Biological Processes			
Trophic Dynamics			
% omnivorous individuals [4]	Cumulative	Increase	1, 2, 3
% invertivorous individuals [5]	Cumulative	Decrease	1, 2, 3
% herbivorous individuals [6]	Cumulative	Decrease	1, 2, 3
% planktivorous individuals [7]	Cumulative	Decrease	1, 2, 3
% top carnivores [8]	Cumulative	Decrease	1, 2, 3
Productivity			
% large individuals	Cumulative	Decrease	1, 2, 3
number of size classes	Cumulative	Decrease	1, 2, 3

[1] Excludes alien or introduced taxa
[2, 3] Potential candidates to be determined
[4] Assesses the degree that the food base is altered to favor taxa that can digest considerable amounts of both plant and animal foods

[5] Evaluates the degree that the invertebrate assemblage is degraded by environmental changes
[6] In tropical fresh waters herbivores usually occurred in least degraded sites (Lyons et al., 1995)
[7] Evaluates the degree that the plankton assemblage is degraded by environmental changes
[8] These taxa indicate a trophically diverse assemblage. They are susceptible to the bioaccumulation of persistent toxins and, being typically long-lived taxa, they are affected by long-term physical and chemical habitat alterations. They are also popular game taxa, and therefore susceptible to exploitation and hatchery stressors.

Macrophyte Research Strategy

Research priorities for creating a coral reef macrophytes index of biological integrity are outlined in Table 13. Macrophytes in tropical marine waters may be comprised of vascular plants (e.g., seagrasses) and algae (e.g., sessile and drift). Macrophytes are a vital resource because of their value as extensive primary producers; a food source; a habitat and nursery area for commercially and recreationally important fish species; as a protection against shoreline erosion; and as a buffering mechanism for excessive nutrient loadings. Because of the combined high productivity and habitat function of the plant assemblage, any or all of the other coral reef biota can be affected by the presence or absence of macrophytes.

Some of the advantages of using marine macrophytes in biological surveys are as follows (Gibson et al., 1997).

- Vascular plants are a sessile assemblage. There is essentially no mobility to rooted vascular or holdfast-established algal plant communities, so expansion or contraction of seagrass beds can be readily measured as an environmental indicator.

- Sampling frequency is reduced because of the relatively low assemblage turnover relative to other biota such as benthic invertebrates or fish.

- Taxonomic identification in a given area is cumulatively consistent and straight forward.

Some of the disadvantages of macrophyte surveys are as follows (Gibson et al., 1997).

- Relatively slow response by the plant assemblage to perturbation makes this a delayed indicator of water quality impacts. This could be critical if prompt management responses are needed.

- Successional blooms of some macrophytes means seasonal cycles need to be identified and accommodated by the survey schedule to avoid misinterpretation of data and false assumptions of water quality impacts.

- Changes in abundance and extent of submerged macrophytes are not necessarily related to changes in water quality.

Table 13. Research priorities for creating a coral reef macrophytes index of biological integrity. Percent sign (%) denotes relative abundance (number of individuals of one taxa as compared to that of the whole assemblage). Cumulative = cumulative human-induced disturbance (i.e., a combination of factors that could include (but is not limited to) fishing, increased temperature and turbidity, chemical contaminants, sedimentation, altered flow regimes, pesticides, nutrients, metals, sediments, and/or bacteria. To reach metric status attributes need the following research: 1 = a quantitative dose-response change in attribute value documented and confirmed across a gradient of human influence that is reliable, interpretable and not swamped by natural variation; 2 = calibration for specific region/location; 3 = transformation. In addition, the entire IBI needs index development (an interpretive framework) that will result in the calculation of a simple numerical score for a particular site, which can then be compared over time or with other similar sites. Attributes can be applied to all tropical seas.

Organizing Structure Attributes	Hypothetical Response Specificity	Hypothetical Response	Research Needs
Community & Assemblage Structure			
Taxa richness			
Total taxa richness (number of taxa/sample)	Cumulative	Decrease	1, 2, 3
Percent cover	Nutrients	Increase	1, 2, 3
Dominance			
% dominant taxa	Nutrients	Increase	1, 2, 3
Taxonomic Condition			
Sensitivity (tolerants and intolerants)			
Number of sediment-intolerant taxa [1]	Sediment	Decrease	1, 2, 3
% sediment-tolerant taxa [2]	Sediment	Increase	1, 2, 3
Individual condition			
Contaminant levels			
Plant tissue nitrogen isotope ratios	Fecal waste	Increase	1, 2, 3
Biological Processes			

Productivity			
Primary productivity (Pmax)	Nutrients	Increase	1, 2, 3
C:N:P content of algae	Nutrients	Increase	1, 2, 3
Alkaline phosphatase assay	Nutrients	Increase	1, 2, 3

[1] Potential candidates include: to be determined
[2] Potential candidates in the Indo-Pacific include: the blue-green *Lyngbya majuscula*, and three red algae *Tolypiocladia glomerulata, Amansia glomerata* and the articulate coralline *Jania sp* (R. T. Tsuda, University of Guam, pers. comm.).

Phytoplankton Research Strategy

Research priorities for creating a coral reef phytoplankton index of biological integrity are outlined in Table 14.

The advantages of using phytoplankton include the following (Gibson et al., 1997).

- Phytoplankton provide a notable indication of nutrient enrichment in marine environments (as do other attributes). Changes in nutrient concentrations can result in long-term changes in assemblage structure and function and planktonic primary producers are one of the earliest assemblages to respond.

- Changes in phytoplankton primary production will in turn affect higher trophic levels of macroinvertebrates and fish.

- Many governments routinely monitor [chlorophyll a] as part of water quality monitoring due to the ease and relatively low cost of analysis.

- Phytoplankton have cumulatively short life cycles and rapid reproduction rates making them valuable indicators of short-term impact.

The disadvantages associated with using phytoplankton include the following (Gibson et al., 1997).

- The fact that phytoplankton are subject to rapid distribution with the winds, tides, and currents means they may not remain in place long enough to be source identifiers of short-term impacts. This problem is compounded by the ability of some phytoplankton to synthesize atmospheric sources of nitrogen, thus confounding the identification of runoff sources of nutrients and the resultant changes in the coral reef biota.

- Taxonomic identification of phytoplankton can be difficult and time-consuming.

- Competition by macrophytes, higher respiration rates, and increased grazing by zooplankton may counteract increased phytoplankton biomass resulting from nutrient enrichment. These reasons argue for investigating phytoplankton and zooplankton together as biological indicators.

- Phytoplankton can undergo blooms, the causes of which might be indeterminate, at varying frequencies.

Table 14. Research priorities for creating a coral reef phytoplankton index of biological integrity. Percent sign (%) denotes relative abundance (number of individuals of one taxa as compared to that of the whole assemblage). Cumulative = cumulative human-induced disturbance (i.e., a combination of factors that could include (but is not limited to) fishing, increased temperature and turbidity, chemical contaminants, sedimentation, altered flow regimes, pesticides, nutrients, metals, sediments, and/or bacteria. To reach metric status attributes need the following research: 1 = a quantitative dose-response change in attribute value documented and confirmed across a gradient of human influence that is reliable, interpretable and not swamped by natural variation; 2 = calibration for specific region/location; 3 = transformation. In addition, the entire IBI needs index development (an interpretive framework) that will result in the calculation of a simple numerical score for a particular site, which can then be compared over time or with other similar sites. Attributes can be applied to all tropical seas.

Organizing Structure Attributes	Hypothetical Response Specificity	Hypothetical Response	Research Needs
Community & Assemblage Structure			
Taxa richness			
Total taxa richness (number of taxa/sample)	Cumulative	Decrease	1, 2, 3
Dominance			
% dominant taxa	Nutrients	Increase	1, 2, 3
Taxonomic Condition			
Sensitivity (tolerants and intolerants)			
Number of intolerant taxa [1]	Cumulative	Decrease	1, 2, 3
% tolerant taxa [2]	Cumulative	Increase	1, 2, 3
Biological Processes			
Productivity			
Phytoplankton [chlorophyll a]	Nutrients	Increase	1, 2, 3
Cyanobacterial blooms	Nutrients	Increase	1, 2, 3

[1, 2] To be determined

Zooplankton Research Strategy

Research priorities for creating a coral reef zooplankton index of biological integrity are outlined in Table 15. Zooplankton consist of two basic categories: holoplankton which spend their entire life cycle as plankton, and meroplankton which are only plankton while in the larval life stage. Holoplankton are characterized by rapid growth rates, broad physiological tolerance ranges, and behavioral patterns which promote their survival in marine waters. The calanoid copepods are the numerically dominant group of the holoplankton, and the genus *Acartia* (*A. tonsa* and *A. clausi*) is the most abundant and widespread. *Acartia* is able to withstand fresh to hypersaline waters and temperatures ranging from 0° to 40° C. The meroplankton are much more diverse than the holoplankton and consist of the larvae of polychaetes, barnacles, mollusks, bryozoans, echinoderms, and tunicates as well as the eggs, larvae, and young of crustaceans and fish. Zooplankton populations are subject to extensive seasonal fluctuations reflecting hydrologic processes, recruitment, food sources, temperature, and predation. They are of considerable importance as the link between planktonic primary producers and higher carnivores. As such, they are also early indicators of trophic shifts in the aquatic system (Gibson et al., 1997).

Advantages of zooplankton sampling are similar to phytoplankton and include the following (Gibson et al., 1997).

- The rapid turnover of the assemblage provides a quick response indicator to water quality perturbation. The challenge will be to sort out the rapid turnover due to human influences from the rapid and normal seasonal turnover in species composition and abundances.

- Sampling equipment is inexpensive and easily used.

- Compared to phytoplankton, sorting and identification is fairly easy.

Some limitations of using zooplankton in biosurveys include the following (Gibson et al., 1997).

- The lack of a substantial data base for most regions.

- The high mobility and turnover rate of zooplankton in the water column. While this permits a quick response by zooplankton to environmental changes on the one hand, it also increases the difficulty of evaluating cause and effect relationships for this assemblage.

Table 15. Research priorities for creating a coral reef zooplankton index of biological integrity. Percent sign (%) denotes relative abundance (number of individuals of one taxa as compared to that of the whole assemblage). Cumulative = cumulative human-induced disturbance (i.e., a combination of factors that could include (but is not limited to) fishing, increased temperature and turbidity, chemical contaminants, sedimentation, altered flow regimes, pesticides, nutrients, metals, sediments, and/or bacteria. To reach metric status attributes need the following research: 1 = a quantitative dose-response change in attribute value documented and confirmed across a gradient of human influence that is reliable, interpretable and not swamped by natural variation; 2 = calibration for specific region/location; 3 = transformation. In addition, the entire IBI needs index development (an interpretive framework) that will result in the calculation of a simple numerical score for a particular site, which can then be compared over time or with other similar sites. Attributes can be applied to all tropical seas.

Organizing Structure Attributes	Hypothetical Response Specificity	Hypothetical Response	Research Needs
Community & Assemblage Structure			
Taxa richness			
Total number of larval fish families	Cumulative	Decrease	1, 2, 3
Dominance			
% dominant larval fish family	Cumulative	Increase	1, 2, 3
Taxonomic Composition			
Sensitivity (tolerants and intolerants)			
Larval fish and other reef taxa families[1]	Cumulative	Decrease	1, 2, 3
Individual condition			
Anomalies			
% deformity in larval fish	Cumulative	Increase	1, 2, 3
Contaminant levels			
Coral egg-sperm interactions	Cumulative	Decrease	1, 2, 3
Coral embryological development	Cumulative	Decrease	1, 2, 3
Coral larval settlement & metamorphosis	Cumulative	Decrease	1, 2, 3
Coral acquisition of zooxanthellae	Cumulative	Decrease	1, 2, 3

[1] To be determined

Using IBIs to Diagnose Causes of Biological Degradation

In previous papers, we have suggested that useful coral reef metrics within an IBI should show response specificity; that is, a response which is indicative of a relatively small number or numerous stressors (Jameson et al., 1998; Erdmann and Caldwell, 1997). A coral reef IBI containing a suite of metrics with varying levels of specificity would insure that known as well as unknown human stressors are detected. Such response specificity would obviously be useful in allowing reef managers to pinpoint the cause(s) of change on their reefs in order that management actions can be taken to ameliorate the perceived stress. Typical human reef stressors can be categorized hierarchically; physical stress (e.g., blast fishing, coral mining, anchor and diver damage), water quality degradation/eutrophication stress *sensu* Tomascik and Sander (1987a & b; i.e., a combination of nutrient enhancement, increased sedimentation, and introduction of marine toxins), biological infestations (e.g., coral diseases), and even ecosystem shifts due to overfishing. At the more proximal level, it is possible to differentiate specific stresses such as heavy metal pollution, or even more specifically, mercury (Hg) pollution. At what level can we reasonably expect a coral reef IBI to differentiate between stressors?

Even at this relatively early stage of reef biomonitoring, it is certainly possible to use currently-accepted coral reef attributes to differentiate between broad categories of reef stressors. As an example, a recent study in the Pulau Seribu Archipelago in Indonesia revealed a drastic reduction in the percentage of live coral cover on a number of reefs during the ten-year period between UNESCO-sponsored surveys (Brown, 1986; Soemodihardjo, 1999). Early speculation as to the cause of the degradation by the coral ecologists in the survey team centered upon *Acanthaster plancii* infestation, but a strongly pronounced size-class truncation of reef-flat stomatopod assemblages on the same reefs suggested that the cause was more likely a “pulse” disturbance in 1991-1992, probably El Niño-related heat stress (Erdmann and Sisovann, 1999). In this case, the inclusion of stomatopods in the reef monitoring protocol enabled researchers to differentiate between reef degradation due to biological infestations versus that due to a short-term physical stress.

At the more proximal level, few coral reef attributes seem able to differentiate specific stressors, such as mercury pollution versus petroleum hydrocarbon pollution. This fact reinforces the importance of collecting ancillary information on human activity and influences to aid in the interpretation of the biological signal (just as the doctor wants to know things about a person's lifestyle as well as the metabolic and physiological measures of their health).

Examples of those indicator organisms which are extremely response specific include the gastropod imposex response to tributyl tin contamination (Ellis and Pattisina, 1990), changes in foraminiferal assemblages from algal symbiont-bearing taxa to heterotrophic taxa in response to nutrient enhancement (Cockey et al., 1996), changes in the size, density, and starch sheath of zooxanthellae in giant clams in response to nutrient enhancement (Ambariyanto and Hoegh-Guldberg, 1996; Belda-Baillie et al., 1998), and developmental defects in reef fishes as a result of PCB or dioxin contamination (Lisa Kerr, University of Maryland, Baltimore, USA, pers. comm.).

However, many other proposed coral reef indicator organisms are considerably less specific in their response, particularly with regard to water quality degradation. As an example, stomatopod abundance, diversity and recruitment are reduced by a variety of marine pollutants, including petroleum hydrocarbons (Steger and Caldwell, 1993), heavy metals (Erdmann and Caldwell, 1997), domestic sewage (Erdmann, 1997; Gajbhiye et al., 1987) and ammonium and phosphate enrichment (ENCORE team, in review). Other promising indicator organisms of water quality deterioration, such as rubble-boring sponges (Holmes, 1997; Holmes et al., 2000) and amphipods (Thomas, 1993), are also sensitive to a range of eutrophication/marine pollution agents.

The issue of response specificity is also of concern in the more developed field of freshwater monitoring (discussed in Johnson et al., 1993; Davis and Simon, 1995; Simon, 1998; Karr and Chu, 1999). Unfortunately, it seems that even freshwater indicator organisms rarely provide such an easily measured, stressor-specific response as gastropod imposex in response to tributyl tin contamination. In freshwater monitoring, the issue of response specificity has been examined primarily at the suborganismal level; for example, changes in enzymatic activity of clams in response to Cu and Zn in power plant effluents (Farris et al., 1988) and changes in hemolymph ion regulation in midges exposed to naphthalene (Darville et al., 1983). Freshwater monitoring has also made extensive use of bioaccumulating indicators, or sentinel organisms, which actually accumulate specific toxins in their tissues (Johnson et al., 1993). While such techniques are preferable to direct chemical analysis of receiving waters in that they assess only those pollutants which are bioavailable and ecologically relevant, they nonetheless require detailed chemical analyses.

We will never have screens for all the thousands of compounds that degrade marine water quality - and if we did we would be neglecting the other 4 major factors listed in Table 2. We can and must work on the most important response specific screens and use general screens to find the others (rather than working on all the individual compounds first).

In general, the coral reef attributes listed in Tables 10-15 and in Jameson et al. (1998) are often able to differentiate between broad categories of stressors, but with a few notable exceptions, do not show specific responses to individual stressors (particularly those involved in water quality degradation). With further research, it may become possible to develop a multimetric index that includes a range of attributes with unique responses to a wide variety of possible stressors. Several workers have argued that it is ecologically unrealistic to attempt to monitor such stresses as nutrient enhancement and introduction of marine toxins in isolation, as they almost invariably occur together, and likely with additive or synergistic effects (Tomascik and Sander, 1987a; Smith et al., 1988; Karr and Chu, 1999).

Given these considerations, a “best course of action” for the future of coral reef assessment may include development of multimetric indexes that address the five attributes of coral reef resources that are altered by cumulative effects of human activity (Table 2) and that use the framework outlined in Figure 1 for basic reference. Indexes should include a taxonomically-diverse group of indicator organisms that show a unique response to several different broad categories of stressors, as well as a select few organisms which are able to detect specific stresses of particular concern to individual monitoring programs (Tables 10-15). For example, a “generic” multimetric index of broad applicability for pilot monitoring studies in most coral reef ecoregions might include metrics based on a variety of pollution-sensitive coral rubble cryptofauna (e.g., boring sponges, stomatopods and/or amphipods), specific bioindicators of nutrient enhancement (e.g., giant clam zooxanthellae, foraminifera, nitrogen isotope techniques), indicators of fishing (e.g., monitoring of reef food-fish relative abundance), and several of the more commonly used parameters of hard coral “health” (e.g., colony size structure, mortality index, coral damage index). In situations where stress is detected with the multimetric index, supplemental analyses of the factors listed in Table 2 may also be required to pinpoint the stressor(s) to the coral reef. Analysis of regional human activity in the adjacent terrestrial landscape will more likely be associated with changes in biological condition than a few narrow chemical parameters (J. R. Karr, personal observation). Indeed, Risk et al. (1994; in press) have argued that reef monitoring programs are most effectively designed as a combination of “low-tech” and “high-tech” science, with low-tech biomonitoring techniques used to detect ecologically-relevant stresses to the reef, followed by high-tech geochemical analytical techniques to determine the exact stressor(s).

Well designed coral reef IBIs have the potential to give a reliable early warning signal of general reef impairment. However, to diagnose what is actually causing the impairment requires focusing in on the raw data of the individual metrics within the IBI (especially the various response specific indicators such as the coral damage index for physical damage, nitrogen isotope ratios in tissue for sewage detection, bioaccumulation in molluscs and corals for metal detection, and gastropod imposex for tributyltin detection). Habitat characterization measurements that are collected as part of the IBI process will also be critical in diagnosing specific causes of degradation. These measurements include but are not limited to: coral reef area, geomorphometric classification, habitat type, watershed land use, population density, pollution discharges, algal cover, salinity, conductivity, dissolved oxygen, temperature, pH, turbidity, Secchi depth, nutrients, organics, metals, depth, sediment grain size, total volatile solids, total organic carbon, acid volatile sulfides, sediment reduction-oxidation potential, and sediment contamination.

An extremely important practice to maximize the utility of the information generated in the IBI process and to expedite decision-making, is to always retain the raw data. These files can be used to translate historical data sets into present indexes for temporal continuity, and even more importantly, they can provide an interpretation and potential diagnosis for management action when a particular site is being evaluated.

Because a multimetric index (IBI) is a single numeric value, critics charge that the information associated with the metrics is somehow lost in calculating the index itself (USEPA, 1985; Suter, 1993). Multimetric indexes condense, integrate, and summarize — they don't lose — information. They comprise the summed response signatures of individual metrics, which individually point to likely causes of degradation at different sites (Karr et al., 1986; Yoder, 1991; Yoder and Rankin, 1995b). Although a single number, the index, is used to rank the condition of sites within a region, details about each site — expressed in the values of the component metrics — are retained

(Simon and Lyons, 1995). It is straightforward to translate these numeric values into words describing the precise nature of each component in a multimetric evaluation. These descriptions, together with their numeric values, are available for making site-specific assessments, such as pinpointing sources of degradation (Yoder and Rankin, 1995a) or identifying which attributes of a biotic assemblage are affected by human activities (Karr and Chu, 1999)

Rigorously constructed multimetric indexes are robust measurement tools. Although their development and use can sometimes be derailed, the failure of a monitoring protocol to assess environmental condition accurately or to protect coral reefs usually stems from conceptual, sampling, or analytical pitfalls. Multimetric indexes can be combined with other tools for measuring the condition of ecological systems in ways that enhance or hinder their effectiveness. Like any tool, they can be misused. That multimetric indexes can be, and are, misused does not mean that the multimetric approach itself is useless (Karr and Chu, 1999).

For best results the following pitfalls should be avoided (Karr and Chu, 1999).

Conceptual

- Excessive dependence on theory
- Narrow conceptual framework
- Failure to account for a gradient of human influence
- Expectation of simple chemical (or other) correlations
- Poor definition or misuse of reference condition

Sampling

- Inadequate design
- Too many or too few data
- Misunderstanding of the sources of variability
- Failure to sample across a gradient of human influence
- Inappropriate use of probability-based sampling

Analytical

- Use of incompatible data sets

- Failure to keep track of sources of variability
- Failure to understand cumulative ecological dose-response curves
- Inattention to important signals, such as rare species
- Failure to test metrics

The primary strengths of multimetric index development and use include:

- it is a rational, consistent way to reduce large amounts of data to meaningful interpretations;
- it is a quantitative treatment of the observations which permits statistical assessments;
- interpretive bias is reduced in the treatment of the data; and
- it helps us to target components and gives context to the data that provides new understanding and better information for effective communication.

In closing, the IBI approach helps us to find more "information" in the data that we have collected and it gives us a formal framework to use that information, something that was not available in the past when many researchers simply collected "data" and produced uninspiring summaries of those data that were largely ignored by those working at the policy level.

Next Steps

To help to coordinate and guide future research, this paper and progress on implementing the coral reef IBI research strategy will be widely disseminated to the research community via the internet at the USEPA coral reef web site (http://www.epa.gov/owow/oceans/coral). Efforts will be made by U.S. government funding agencies to implement this research strategy for coral reefs under U.S. jurisdiction. Jameson et al., (in prep.) are in the process of designing a coral reef classification system for reefs under U. S. jurisdiction to determine reference conditions and regional ecological expectations (Step 1-Table 4). IBI 's will be tested and refined via pilot programs on U.S. coral reefs in the Caribbean and Pacific. Hopefully, other nations will join in this endeavor to fund and implement aspects of this research strategy.

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Charting a Course Toward Diagnostic Monitoring
Appendix 1.

New coral reef attributes supplementing the review by Jameson et al. (1998). References in bold specifically mention the metric potential of the attribute, those in plain text are primary literature which supports the utility of the attribute.

Attribute	Protocol	Region	References
Coral population colony size structure	Colony size frequencies of coral populations can be modeled by log normal distributions. Under "normal" conditions, colony size structure is skewed to the right, with high frequencies of small coral colonies. Evidence from a comparison of coral colony size frequencies from degraded and "less degraded" reefs suggests that under deteriorating environmental conditions, modal coral colony size increases, indicating changes in mortality and recruitment patterns that result in relatively fewer small and more large coral colonies.	Caribbean Pacific Indian	**Bak and Meesters, 1998**
Coral morphology triangles	Adapted from a terrestrial plant ecology methodology, this technique classifies coral reefs according to their conservation value using r-K-S (ruderal/competitor/ stress-tolerator) ternary diagrams based upon the relative abundance of standardized coral morphology categories on each reef. Technique has been calibrated for Indonesian reefs, and assigns a conservation value to each reef based upon its position in an r-K-S ternary diagram. Has the advantage that it does not require coral taxonomic knowledge, but instead utilizes the considerable database of life forms transect data which is commonly collected in monitoring programs of many Indo-Pacific countries.	Caribbean Pacific Indian	**Edinger and Risk, 1999**
Coral fecundity, fertilization rate	Recent results from the large-scale ENCORE experiment show conclusively that increased ammonium and phosphate levels in reef environments have strongly negative effects on coral fecundity and fertilization rate. In experiments with several acroporid species, corals subject to increased nutrient levels had significantly smaller and fewer eggs and less testes, and fertilization rates were reduced. Though the authors did not suggest that these coral parameters be used as a bioassay of eutrophication, these results corroborate earlier suggestions that coral fecundity and fertilization rate may be used as sensitive biocriteria.	Caribbean Pacific Indian	Ward, 1997 Ward and Harrison, 1999
Coral settlement rate	Further results from the ENCORE experiment show that settlement tiles placed in reef environments subject to increased levels of ammonium and of ammonium and phosphate have significantly reduced settlement of coral spat. Though not yet developed into a biomonitoring protocol, use of settlement tiles for water quality monitoring of nutrient inputs to reef environments is a promising technique worthy of further biocriteria research.	Caribbean Pacific Indian	Ward and Harrison, 1997 Ward and Harrison, 1999

Bioaccumula-tion in sponges	The efficient filter feeders and lipid rich common sponges *Chondrilla nucula* and *Aplysina fistularis* are used as coral surrogates to monitor chemical contaminants in the EPA coral disease survey in the Florida Keys National Marine Sanctuary.	western Atlantic (Florida)	**D. L. Santavy**, U.S. EPA Office of Research and Development, Gulf Ecology Division, pers. com.
Giant clam zooxanthellae	Giant clam zooxanthellae populations are generally considered to be N-limited. Results from the ENCORE experiment demonstrate conclusively that zooxanthellae in *Tridacna maxima* show a number of interrelated responses to increased ammonium, including an increase in the density and chlorophyll content of zooxanthellae, a decrease in the average size of zooxanthellae, and a decrease in the starch sheath surrounding the pyrenoid of the zooxanthellae chloroplasts. This sensitive response of giant clam zooxanthellae populations make them an excellent candidate for development as bioindicators of nutrient enrichment. Monitoring the size of clam zooxanthellae seems particularly promising, as it is quick, easy and does not harm the clam.	Pacific Indian	**ENCORE team, in review** Ambariyanto and Hoegh-Guldberg, 1996 Ambariyanto, 1996 Belda et al., 1993b Belda-Baillie et al., 1998
Giant clam shell growth rate	Further results from the ENCORE experiment show that giant clams (*T. maxima*) exposed to increased levels of ammonium have significantly increased shell growth rates. This parameter is easy and inexpensive to monitor, and with proper calibration could be an excellent biocriteria for monitoring programs concerned with nutrient enrichment.	Pacific Indian	Ambariyanto, 1996 Belda et al., 1993a **ENCORE team, in prep**
Coral Damage Index	Sites are listed as “hot spots” (in need of management attention) if in an transect the percent of broken coral colonies is greater than or equal to 4% or if the percent cover of coral rubble is greater than or equal to 3%.	Red Sea	**Jameson et al., 1999**
Vibrio shiloi as causative agent of *Oculina patagonica* bleaching	Studies using the coral *Oculina patagonica* have linked coral bleaching with a bacterial disease caused by *Vibrio shiloi.* The disease can be blocked by antibiotics. Elevated seawater temperature is a critical factor for this disease. From 16-20°C the disease does not occur, whereas from 25-30°C even a few *Vibrio shiloi* can cause the disease. Increased temperature without the bacteria is insufficient to cause bleaching because antibiotics prevent the bleaching even at elevated seawater temperatures. Elevated temperature triggers bacterial adhesion to coral surface and allows infection to proceed.	Mediterranean coast of Israel.	Rosenberg and Loya, 1999
Coral stress using gene expression	Uses recent advances in molecular biology to visualize changes in scleractinian mRNA abundance. Stressor-specific probes for mRNA are being developed for quantifying the intensity of stress in corals and diagnosing the most likely stressors. Transplantation experiments will be conducted to examine how stressors in natural populations induce gene expression.	western Atlantic (Florida)	**Snell, in progress**

FoRAM (Foraminifers in Reef Assessment Monitoring)	FoRAM consists of a three tiered protocol. Number of tiers used depends on the region being assessed and questions being asked. 1. Sediment constituent analysis, which can address questions of historical change and reference-site suitability. 2. Analysis of live larger foraminiferal assemblages, which can indicate the suitability of sites for organisms with algal symbionts. 3. Analysis of *Amphistegina* populations, including abundance, presence of bleaching, and other evidence of specific stressors to which these foraminifers respond similarly to corals.	western Atlantic (Florida)	**Hallock, 1996** **Cockey et al., 1996** **Hallock, 2000**
Molecular Biomarker System (MBS)	Uses a MBS that assays specific cellular and molecular parameters, to assess the physiological status of coral challenged by heat stress. The MBS distinguished the separate and combined effects of heat and light on the two coral symbionts, a scleractinian coral and a dinoflagellate algae (zooxanthellae). This technology aids in the accurate diagnosis of coral condition because each parameter is physiologically well understood. The MBS technology is reportedly relatively inexpensive, easy to implement, precise, and can be quickly adapted to a high-throughput robotic system for mass sample analysis.	western Atlantic (Florida)	**Downs et al., in press**

Reef Check '97, with notes on recent Reef Check protocol changes	In Reef Check '97 (Hodgson, 1999) twenty-five worldwide and regional "health indicators" were used by trained volunteer recreational divers to provide information about the effects of human activities on coral reefs. This unprecidented effort got hundreds of people out onto reefs using one method to monitor coral reefs and helped raise awareness about coral reefs. The world's oceans were divided into Indo-Pacific, Red Sea and Caribbean (special regional indicators were chosen for biogeographic margins e.g. Arabian Gulf, Hawaii and the E. Pacific). Sites believed to be least affected by human activities and having the highest percentage of seabed covered by living coral and the highest populations of indicator fish and other invertebrates were selected for monitoring. The protocol included the collection of 4 types of data: a site description; a fish survey; an invertebrate survey and a substrate survey. The underwater surveys were made along the 3 and 10 m depth contours. The following conclusions were drawn from the study. Results showed that no reefs had high numbers of most indicator organisms, suggesting to the author that few, if any, reefs have been unaffected by fishing and gathering. The low percentage cover of pollution indicators was taken to suggest that sewage pollution is not a serious problem a most of the sites (biased toward perceived good condition). Technical recommendations regarding the use of Reef Check for long-term monitoring are given in Hodgson and Stepath (1999). Hodgson (1999) mentions some ways the protocols could be improved (i.e., establishing sample size goals and obtaining historical baseline data). Improvement and refinements in the program are also discussed in Hodgson (2000). We suggest the protocols could also be improved by: 1. Verifying data quality with an analysis of the variation between teams in controlled studies. 2. Confirming that a dose-response change in "health indicator" value is reliable, interpretable and not swamped by natural variation; 3. Sampling across a gradient of human influence rather than relying on the perception of participants to select monitoring sites least affected by human activity (or hoping groups will have the time to survey multiple sites representative of moderate and heavy human impacts (Hodgson and Stepath, 1999; Reef Check, 2000)); 4. Classifying sites (before monitoring begins) with respect to similar environmental conditions so appropriate sites can be selected to allow valid comparisons among similar sites (site description sheets prepared by teams are used to compare sites after monitoring (Hodgson and Stepath, 1999; Reef Check, 2000); 5. Resurveying the same sites every year (G. Hodgson, Reef Check, pers. comm.) 6. Calibrating indicators or collecting data on fishing effort or pollution to determine the causes of the degradation. Otherwise the causes of presumed changes (degradation) are assumed; 7. Using minimally degraded reference sites to compare against degraded sites (which in Reef Check are biased towards a perceived less impacted condition); and by 8. Not using the Bray Curtis similarity index to examine the relationships among all sites for six worldwide indicators (Hodgson, 1999) because this index has been shown in independent independetests to fail to discriminate among sites (CAO, 1997). independent tests to fail to discriminate among sites (Cao, 1997).	Indo-Pacific, Red Sea, Caribbean	**Hodgson, 1999** **Hodgson and Stepath, 1999** **Hodgson, 2000** **Reef Check, 2000**

Reef Check Coral Reef Health Index (CRHI)	The CRHI was calculated for six indicators (butterflyfish, Haemulidae grouper, *Diadema*, hard corals and lobster) for 269 sites from 3 regions. The highest mean abundance of an organism recorded at any site in the world was used as the maximum possible value to determine a lower, middle and upper third for 269 sites in 3 regions. Then, for each site, a value of 0-3 was assigned for each indicator depending on the mean abundance in comparison to the cut-off levels for each third. Means in the lower, middle and upper third were assigned a value of 1, 2 and 3 respectively while a mean of zero was assigned a zero (except for *Diadema* where the values were reversed as high numbers are considered to be unhealthy). The CRHI was calculated by adding the 6 values together. The maximum possible CRHI is : 6 indicators X 3 = 18. The mean CRHI values from the study were 3.8, 4.0 and 3.5 respectively for the Indo-Pacific, Red Sea and Caribbean regions, out of a maximum possible CRHI of 18. There was no significant difference among the values from the three regions and the low CRHI scores were assumed to indicate how few sites had high numbers of indicators recorded. The comparison among sites could be improved by classifying sites as mentioned in (2) above. Much early freshwater work to detect the influence of human actions on biological systems emphasized abundance (or population size or density) of indicator taxa, often species with commodity value or thought to be keystone species. Generally, however, population size varies too much even under natural unimpaired conditions to be a reliable indicator of biological condition. Population size changes in complex ways in response to changes in natural factors such as food supply, disease, predators, temperature, salinity and demographic lags. In studies to determine environmental impacts, the interaction between variability and the size of the potential impact (effect size) must also be taken into account, because that interaction affects statistical power (Osenberg et al. 1994). High variation in population size, even in natural environments, interacts in complex ways with changes in abundances stimulated by human actions. Thus it can be very difficult to detect and interpret the effects of human actions even with advanced experimental designs. The minimum level of sampling effort may exceed the planning, sampling, and analytical capability of many monitoring situations. By shifting the focus to better-behaved indicators such as changes in taxa richness, loss of sensitive taxa, or changes in trophic organization, it is possible to develop a clearer and broader understanding of biological changes (Karr and Chu, 1999). Using the highest mean abundance of an organism recorded at any site in the world as the maximum reference condition for sites also disregards the effects of regional, seasonal and environmental factors on species abundance and is probably setting the reference bar too high in some areas and too low in others.	Global	**Hodgson, 1999**
Reef Check Distance-Population Index (DPI)	The DPI was calculated by assigning a score for both population of nearest city and the distance to that city as follows: Population 0-10,000 = 0; 10,000-50,000 = 1; 50,000-100,000 = 2; > 100,000 = 3. Distance > 50 km = 0; 25-49 km = 1; 10-24 km = 2; 0-9 km = 3. The DPI was then calculated as the sum of the population size and distance scores. The higher the index means the site is close to a dense population. The maximum DPI is 6. The CRHI was plotted versus the DPI to show that a sizable number of sites located far from population centers had a low health index. See comments above regarding the applicability of the CRHI.	Indo-Pacific, Red Sea, Caribbean	**Hodgson, 1999**

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